

Progress in Microchannel Steam Reformation of Hydrocarbon Fuels

**2003 Hydrogen and Fuel Cells Merit
Review**

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Approach –2003

- ▶ Confirm benefits of operating steam reformer at higher temperature.
 - Productivity for benchmark fuel increased 3X between 650°C and 850°C.
 - Sulfur tolerance significantly increased.
 - Higher productivity reduces thermal mass → less air and fuel required for startup, reduced losses associated with cycling thermal mass on startup.
- ▶ Operate a low dP steam reformer capable of fast startup
 - Design/build system to achieve fast start while maintaining capability to achieve 78% efficiency during steady-state operation.
 - Fast start to be achieved by maintaining pressure drops low and using large flow of combustion gas. Initial work based on a 650°C reformer in stainless steel.
- ▶ Integrate reformer with WGS and PROX at 2 kWe scale.

Objectives

- ▶ Develop a prototype microchannel-steam reforming based fuel processor at 2 kW_e scale that will meet DOE performance targets when scaled up to 50 kW_e.

Performance Criteria	2003 Projected Performance	2005 DOE Target
Power Density	1191 W/liter	700
Specific Power	376 W/kg	700
Efficiency	78.7%	78.0%
Durability	>1000 hr ^(a)	4000 hr
Transient (10% to 90%)	~5 sec ^(a)	5 sec
Cold Start, 20C	30 sec ^(a)	< 1min

(a) Durability and transient demonstrated for reformer and associated HX only. Cold start estimate is for reformer and HX only.

- ▶ Engage industrial partner(s) to facilitate development of full-scale fuel processing system.
- ▶ Develop reactors, vaporizers, recuperative heat exchangers, and condensers broadly applicable to other fuel processing options.

Project Timeline



FY 1998

Full-size gasoline
vaporizer/combustor
R&D100 Award



FY 1999

Fast SR kinetics
observed in a
microchannel reactor



FY 2000

Designed and built
10 kWe SR with integrated
HX network



FY2001

10 kWe reactor testing
First "low dP" vaporizers
Modular test stand established



FY 2002

SR fuel flexibility, durability testing
WGS/PROX catalyst studies
Differential temperature reactor concept
SR/WGS/PROX initial integration
Full-scale low dP vaporizers delivered



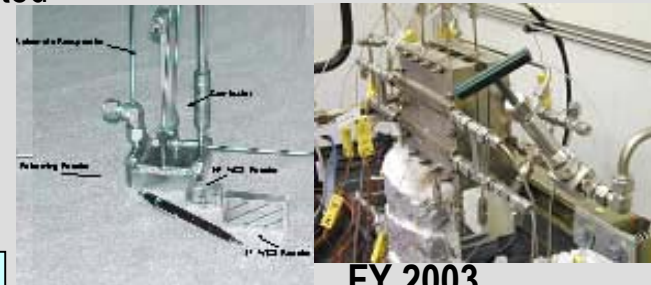
Engineered catalyst,
reactor
development

Feasibility of rapid start
capability

Sulfur management

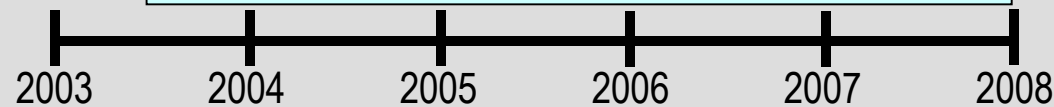
Integrated reformer/fuel cell
at ~2 kWe

Collaborate with industrial partner(s) on
manufacturing, field testing, lifetime, controls



FY 2003

Investigate improved steam
reforming kinetics and sulfur
tolerance at high
temperatures. Fast start.
WGS and PROX integration.



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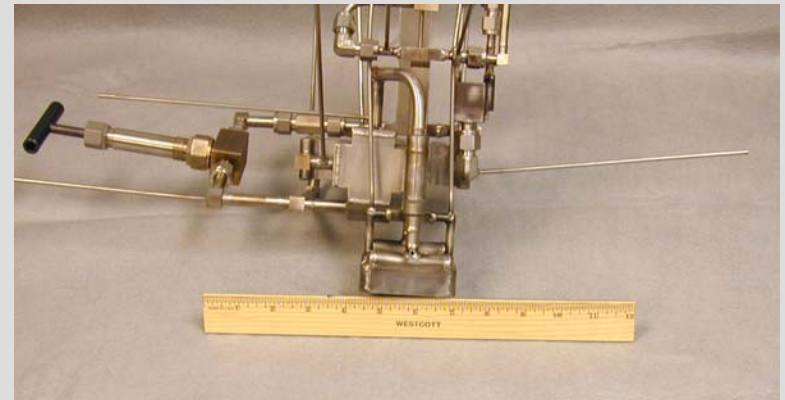
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High Temperature Steam Reforming

Motivation for Investigation

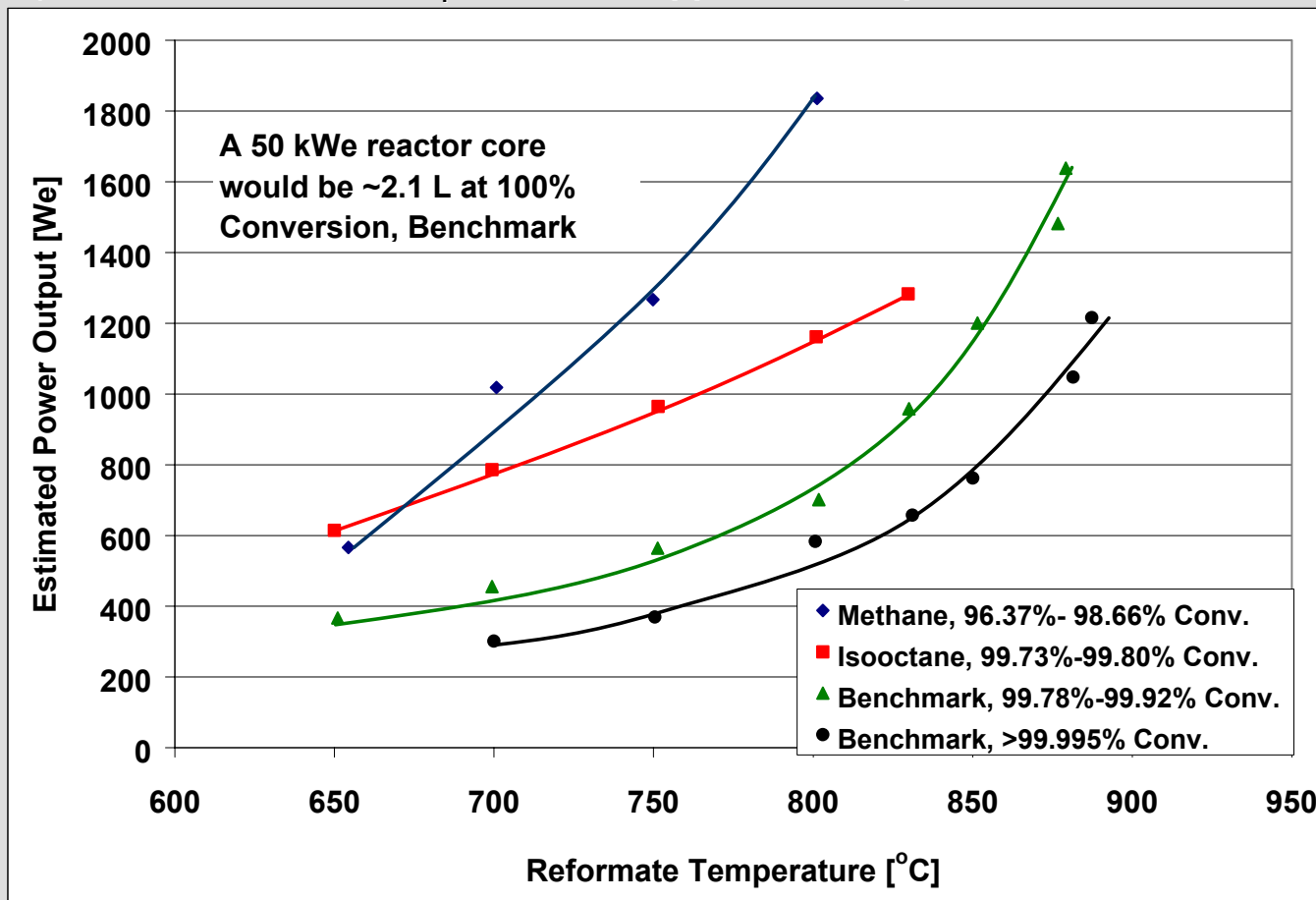
- ▶ **Reduce Reactor Size** - exponential productivity increase with temperature
- ▶ **Reduce Catalyst Quantity** - higher productivity results in less catalyst
- ▶ **Reduce Reactor Startup Mass** — reduction in mass results in less fuel and air compression required during startup. Losses associated with cycling of thermal mass are reduced.
- ▶ **Improve Sulfur Tolerance** — Improve sulfur tolerance may allow sulfur cleanup to be performed on reformatate rather than on liquid fuel.
- ▶ **Evaluate Carbon Deposition Potential** - High temperatures increase potential to deposit carbon by cracking of hydrocarbons at inlet (even if not an equilibrium condition).

Inconel 625 Reformer



Reformer Productivity vs Temperature

(All fuels at 3:1 S:C, CH₄ conv. is % approach to equil., Inconel 625 reformer)



Stability of catalyst productivity verified by measuring the conversion at a reference condition before and after generation of the data for each curve.

Characterization of Sulfur Sensitivity

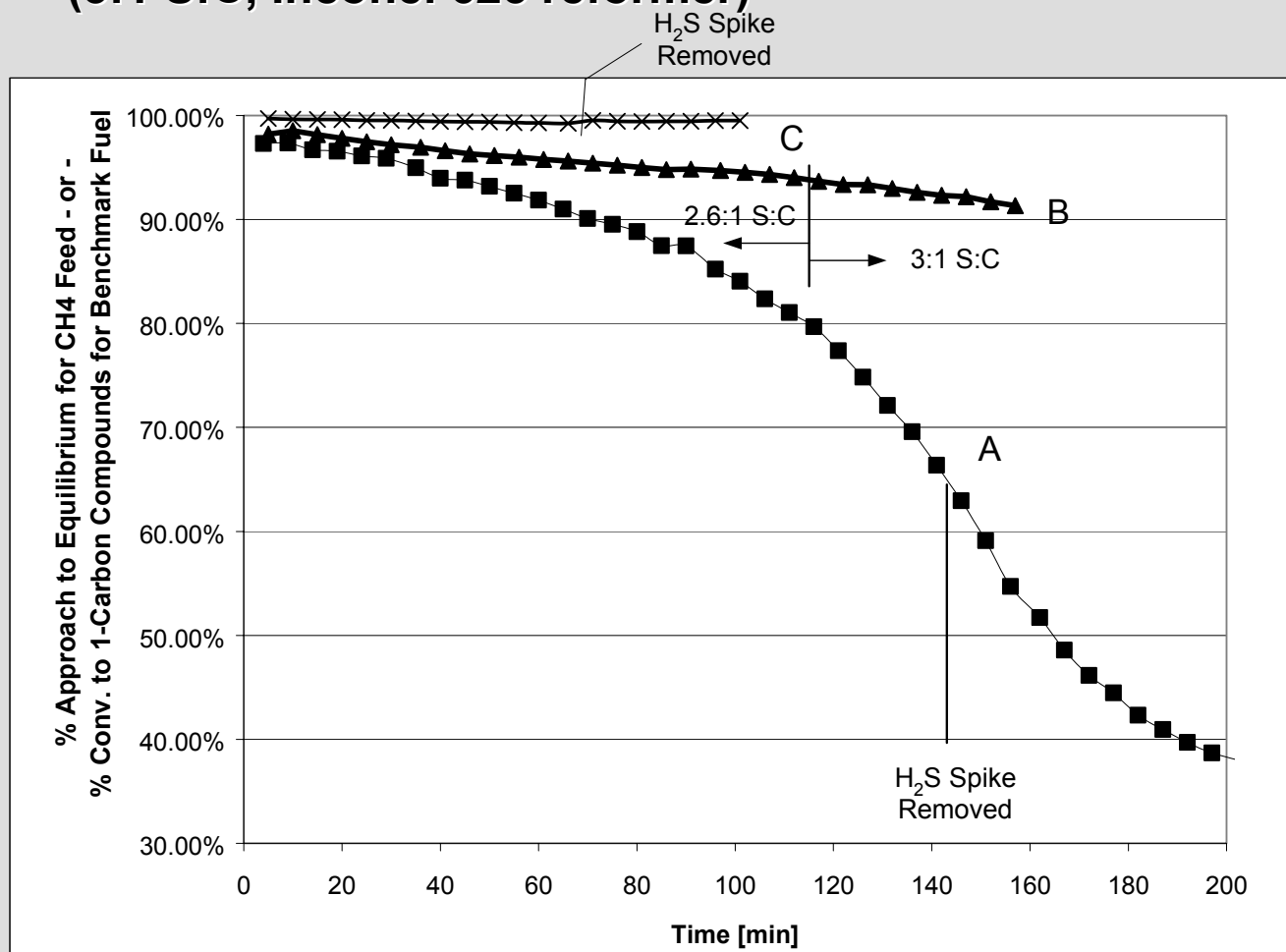
Sulfur Added as H₂S Spike in Methane

(3:1 S:C, Inconel 625 reformer)

A — Reformate outlet at 650°C.
CH₄ with H₂S at 5.4 ppmv
(10 ppmw benchmark equivalent)

B — Reformate outlet 650°C.
Benchmark Fuel w/estimated 10
ppmw S plus CH₄/H₂S spike at 10
ppmw S equivalent.

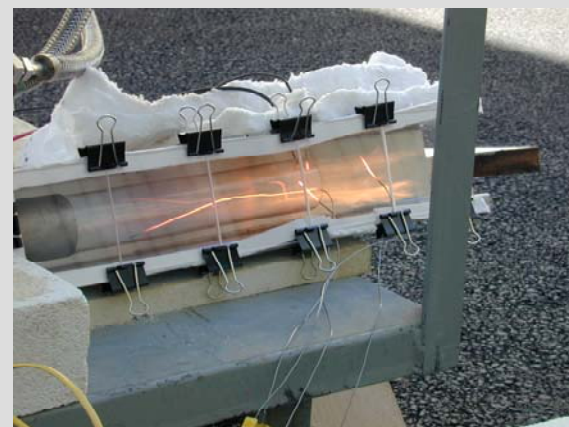
C — Reformate outlet 800°C.
Benchmark Fuel w/estimated 10
ppmw S plus CH₄/H₂S spike at 10
ppmw S equivalent. Sulfur from
previous test (B) not removed prior
to test.



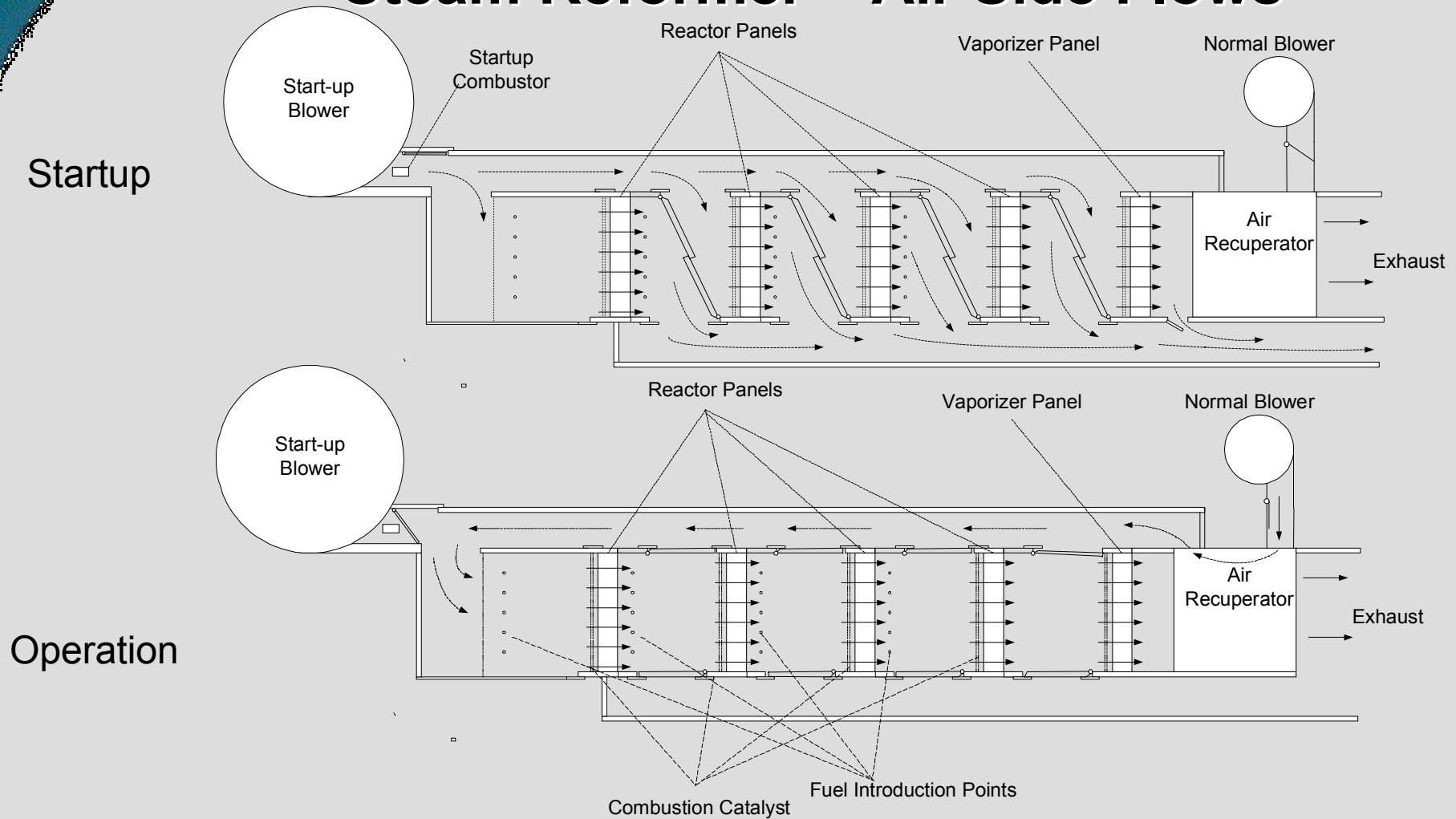
Benchmark Fuel Composition, wt%: 74% Isooctane, 20% Xylenes, 5% methylcyclohexane, 1% 1-Pentene

Fast Start Approach

- ▶ Focus initially on steam reformer, vaporizer, and air and reformat recuperators. Incorporate WGS and PROX in system as development continues.
- ▶ Current system designed to 2 kWe at 650°C reformer temp.
- ▶ High combustion gas flows at low pressure drop heat the reformer, vaporizer and air recuperator.
- ▶ Reformate recuperator is heated via steam from vaporizer.
- ▶ Combustion gas at startup generated by non-catalytic atomized fuel combustion. Combustor tested for isooctane and regular gasoline. Provides 800°C gas in as little as 2 seconds.



Concept for Low Pressure Drop, Rapid-Start Steam Reformer – Air Side Flows



2 kWe Reactor System – Predicted Air Side Pressure Drops

	2 kWe, Steady State Output Condition		30-Second Startup Condition	
Device	Flow [slpm]	ΔP [inches H ₂ O]	Flow [slpm]	ΔP [inches H ₂ O]
Steam Reformer Panel	100	0.65/panel 2.6 total for 4	800	5.2
Water Vaporizer Panel	100	0.28	800	2.2
Air Recuperator	100	1.5 cold side 1.6 hot side	200 (vap exhaust)	3.0
Total	100	6.0	4000	5.2

50kWe-Scale Air Compression Power Implications:

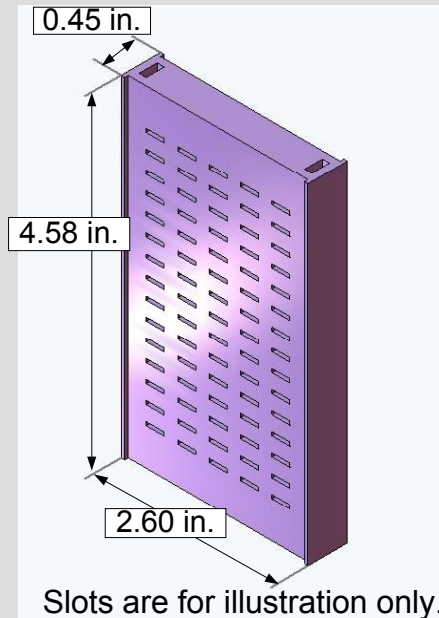
During operation theoretical compressor power is very low (~63W)

During 30 second startup, theoretical compressor power is ~2.2 kW

Fast Start/Low dP Reforming System Components

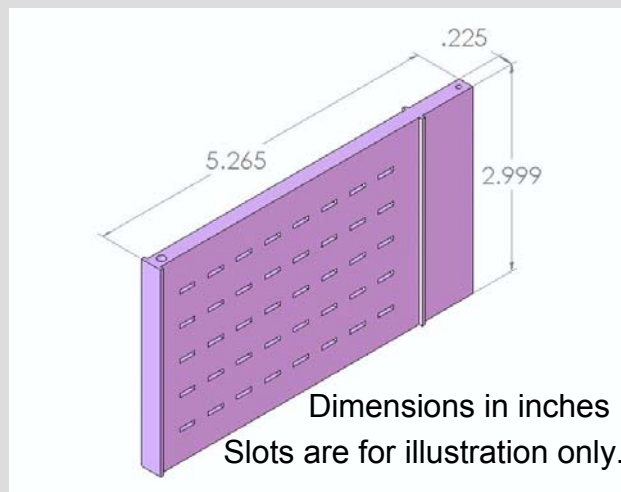
Reformer

- ◆ 4X, ~500 We panels for 2 kWe total at 650°C.
- ◆ Air side ΔP ~0.65 inches water at 500 We output.
- ◆ uniform temperature for all reaction pathways.
- ◆ Stainless construction, ~1534 g for 4 panels.



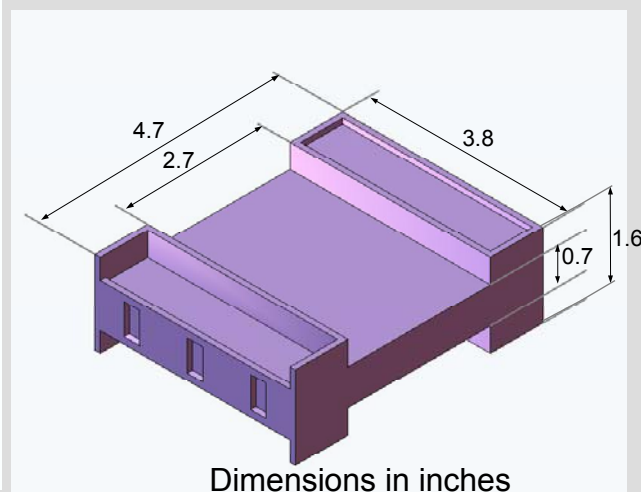
Water Vaporizer

- ▶ Low gas side ΔP , <0.28 in. water
- ▶ Utilizes reactor exhaust
- ▶ Gas inlet/outlet 633°C/146°C
- ▶ Steam outlet 293°C
- ▶ ~400g



Air Recuperator

- ▶ Low ΔP , <2 in. water per pass
- ▶ 87% effective, ~50°C outlet
- ▶ Excellent Turndown
- ▶ ~876 g

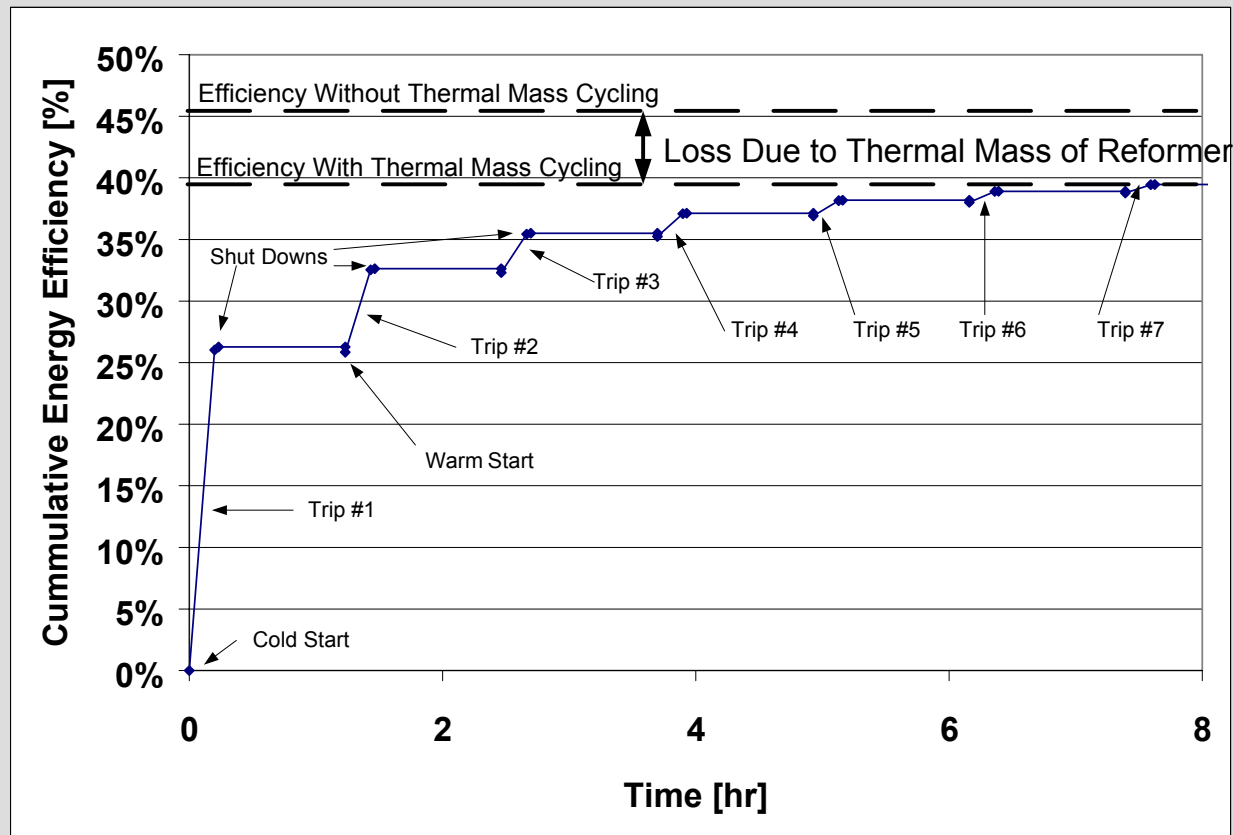


Preliminary Estimate of Efficiency Loss Due to Cycling Thermal Mass of Reformer on Startup/Shutdown Cycles

- ▶ Objective – Assure that the thermal mass associated with the fuel reformer does not impose a severe efficiency penalty when thermally cycled in an automotive application.
- ▶ California Air Resources Board (CARB) real-world study
 - 6.7 Trips per day
 - 61% of cold soaks <1 hour
 - 24.8 mph (average per trip)
 - 46 miles per day
- ▶ Various Assumptions → 7 trips/day separated by 1 hour shutdowns, each trip having 12 minutes at 37% output and 1.9 minutes at 5% output.
- ▶ Estimated masses of components with 3.5 inches conventional insulation, neglect connections.
- ▶ Calculation addresses only thermal mass effect, does not include electrical consumption and exhaust heat losses during startup.

Thermal Mass Startup Penalty

- ▶ Efficiency penalty ~5.2% for one day, ~4.5% for 7 day cycle.
- ▶ At 650°C reformer temperature, reactor is over half the thermal mass.
- ▶ Higher temperature reformer will reduce startup penalty



Plans 2003

- ▶ **Sulfur Testing** - Continue high-temperature sulfur testing to include longer-term testing, with liquid S spikes up to ~30 ppmw.
- ▶ **Improved Catalyst** – Improved catalyst is now available. It is expected to have similar activity at lower cost with increased mechanical and high-temperature durability.
- ▶ **Fast Start Low-dP System**
 - Complete fabrication of stainless reactors and components
 - Conduct initial testing of panel reformer with new catalyst.
 - Generate design input for high-temperature low-dP reformer.
 - Conduct 30-second start tests. Initial tests will not include WGS and PROX.
- ▶ **Move to High-Temperature System** - Revise fast start system design to incorporate high temperature low-dP reformer.
- ▶ **Integrate with WGS and PROX at 2 kWe scale.**

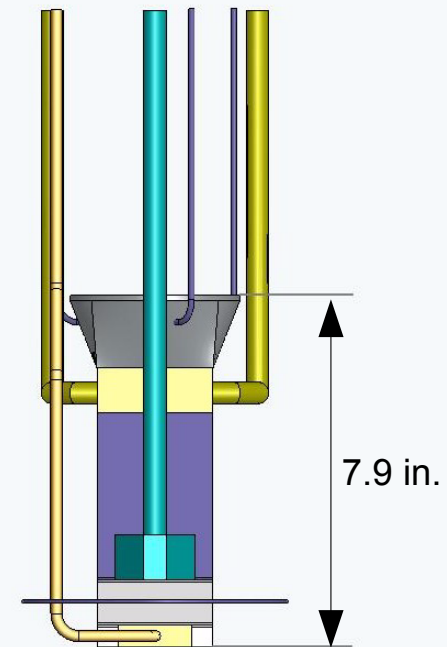
Interactions – Microchannel Recuperator and Mixer Assembly for FASTER Project

Microchannel Recuperator

- 100°C hot end approach
- 3.6 kW duty
- Approx 1.1 kg w/o mixer
- $\Delta P_{\text{cold}} + \Delta P_{\text{hot}} < 0.4$ psi total
- Uniform outlet temperature

Microchannel Mixer

- Uniform outlet temp
- Uniform air-reformate mixture



Interactions, continued

- ▶ Posting on the Federal Business Opportunity Website for *Microchannel Fuel Reformation for Fuel Cell Applications*. – The quality and quantity of responses led to a decision to license intellectual property on a non-exclusive basis.
- ▶ Testing of a microchannel water vaporizer designed for a 50 kWe fuel processor was concluded at McDermott. Similar testing concluded at GTI for boiler application.
- ▶ Finalizing contract with the Gas Technology Institute (GTI) to work with Cleaver-Brooks and GTI to provide a prototype micro-channel economizer for a highly efficient boiler.

Conclusions

- ▶ High Temperature Reforming Benefits
 - >3X productivity when increasing from 650°C to >850°C.
 - Significantly increased sulfur tolerance at 800°C vs 650°C.
 - Reductions in reformer thermal mass
 - Less air and fuel required during startup
 - Penalty associated with cycling thermal mass reduced
- ▶ A low pressure drop steam reformer that can start in 30 seconds appears feasible.
- ▶ Penalty associated with thermal mass of fuel processor is non-negligible. Penalty is reduced significantly by considering multiple restarts in a single day.

Responses to Comments

- *“Given the ...thermal masses, startup energies need to be ...considered, not just start-up times”*: **Calculation performed to assess impact of thermal mass on system efficiency.**
- *“Steam reformer needs to operate at higher temperature thus transition from stainless steel higher-temperature alloys needs to be completed”*: **High-temperature Inconel 625 reactor tested up to 887°C.**
- *“Hydrocarbon conversion levels for liquid fuels are higher than earlier 90% but significant additional improvement is needed” -and- “High temperature reformer operation and demonstration of >99.9% conversion of non-methane hydrocarbons are critical to further progress”*: **Reformer was operated on Benchmark Fuel over a range of temperatures to generate a curve of productivity possible while producing no detectable non-methane hydrocarbons.**